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Semiconductor laser complex dynamics: from optical neurons to optical rogue waves

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The PI has investigated the dynamics of semiconductor lasers with two main goals: i) to advance our understanding of nonlinear and stochastic phenomena and ii) to exploit the laser dynamics for innovative applications. The results of the project were published in 5 high-impact journal papers and were presented as invited or contributed talks in several international conferences and workshops.

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Semiconductor laser complex dynamics: from optical neurons to rogue waves

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CONTENTS

I. SUMMARY

This reports summarizes the main achievements of the project in the period 8/2014-7/2015. We have investigated the dynamics of semiconductor lasers with two main goals: i) to advance our understanding of nonlinear and stochastic phenomena and ii) to exploit the laser dynamics for innovative applications. The results of the project were published in 5 high-impact journal papers and were presented as invited or contributed talks in several international conferences and workshops.

II. INTRODUCTION

Semiconductor lasers are key elements in optical technologies, being coherent light sources in fiber optics communications, optical data storage, life sciences applications, material processing and sensing. They have a huge economic impact and are crucial for the photonics technologies that improve our everyday life style. For developing innovative applications, we need to fully understand nonlinear and stochastic effects.

In the reported period our work has focused on:

1. Optical spikes: we investigated the potential of semiconductor lasers with optical feedback for building "optical neurons" that mimic the spiking output of biological neurons. Optical neurons could be building blocks of future photonics ultra-fast, neuro-inspired information processing systems.

2. Extreme optical pulses and optical rogue waves emitted by optically injected semiconductor lasers: identifying mechanisms triggering these extreme events and mechanisms able to suppress them; developing "big data" analysis tools and early-warning indicators.

Regarding optical neurons, we have investigated, experimentally and numerically, how serial correlations present in the output intensity of a semiconductor laser with optical feedback operating in the low-frequency fluctuations (LFF) regime are affected by direct current modulation. We are interested in the role of current modulation because it represents an input signal, and information about this input can be extracted from the sequence of optical spikes. By using symbolic analysis tools we have previously shown that optical correlations share common statistical features with serial correlations present in sequences of inter-spike-intervals (ISIs) of biological neurons. This similarity opens new avenues, not only in photonics (for using optical neurons as new paradigm for optical computing), but also in neuroscience, because the optical setup provides a fully controllable and inexpensive set-up for exploring neuronal-like behavior, and specifically, the role of external periodic forcing (representing an input stimulus) in neuronal spike sequences.

Regarding extreme optical pulses and rogue waves, as is well known from chaos control theory, the periodic modulation of an appropriate control parameter can suppress chaos; thus, we have investigated if external modulation can also be an effective way to suppress optical rogue waves. We have focused in current modulation, as model predictions could be easily tested experimentally. In injected lasers our model simulations suggest that rogue waves can be fully suppressed by current modulation of appropriated amplitude and frequency. When the pump current is modulated at a frequency close to the laser natural resonance frequency (the relaxation oscillation frequency of the free-running laser), then, the modulation is capable of fully suppressing rogue waves. This is due to the fact that weak modulation increases the regularity of the amplitude of the pulses: the number of large pulses in the time series increases, but at the same time, the pulses are less extreme.

While one of our goals is to find novel data analysis tools capable of anticipating the occurrence of extreme pulses such as rogue waves, as a first step we developed a novel methodology, capable of providing early-warning of abrupt transitions. We tested the method in experimental data recoded from the polarization-resolved output of a Vertical Cavity Surface Emitting Laser (VCSEL) during the polarization switching.

III. METHODS, ASSUMPTIONS, AND PROCEDURES

III.1. Model

The Lang-Kobayashi model was used to study the LFF dynamics with direct current modulation. The model equations are:

$$\frac{dE}{dt} = k(1+\alpha)(G-1)E + \eta E(t-\tau)e^{-i\omega_0\tau} + \sqrt{2\beta_{sp}}\xi, \tag{1}$$

$$\frac{dN}{dt} = \gamma_N(\mu - N - G|E|^2), \tag{2}$$

where E is the optical field, N is the carrier density, τ_p and τ_N are the photon and carrier lifetimes respectively, α is the line-width enhancement factor, G is the optical gain, $G = N/(1+\epsilon|E|^2)$ (with ϵ being a saturation coefficient), μ is the pump current parameter, η is the feedback strength, τ is the feedback delay time, $\omega_0\tau$ is the feedback phase, and β_{sp} is the noise strength, representing spontaneous emission.

For simulating the dynamics with current modulation, the pump current parameter is $\mu = \mu_0 + a\sin(2\pi f_{mod}t)$, where a is the modulation amplitude, f_{mod} is the modulation frequency, and μ_0 is the dc current. Typical parameters

were used in the simulations ($\mu_0 = 1.01$, $\epsilon = 0.01$, $k = 300$ ns^{-1}, $\tau = 5$ ns, $\gamma_N = 1$ ns^{-1}, $\beta_{sp} = 10^{-4}$ ns^{-1}, $\eta = 10$ ns^{-1}, and $\alpha = 4$).

III.2. Experimental setup

The experimental setup used to study the LFF dynamics with direct current modulation is described here. A semiconductor laser (Sony SLD1137VS), with a solitary threshold current I_{th} =28.40 mA, temperature- and current-stabilized with an accuracy of 0.01 C and 0.01 mA, respectively, using a diode laser combi controller (Thorlabs ITC501), emitting at 650 nm, has part of its output power fed back to the laser cavity by a mirror. A 50/50 beamsplitter in the external cavity sends light to a photo-detector (Thorlabs DET210) that is connected to a fast amplifier (FEMTO HSA-Y-2-40), a 1 GHz digital storage oscilloscope (Agilent Technologies Infiniium DSO9104A) and a radio frequency spectrum analyzer (Anritsu MS2651B). A neutral density filter in the external cavity allows to control the feedback power. The laser is operated at 17.00 C and, unless stated, the threshold reduction due to feedback is 7.3%. In the experiment we used three external cavity lengths, corresponding to feedback delay times, τ, of 2.5, 5 and 7.5 ns, and the DC current value was varied in the range between between $1.01I_{th}$ and $1.05I_{th}$.

A bias-tee in the laser mount allows the pump current to be modulated with a sinusoidal signal provided by a 80 MHz waveform generator (Agilent 33250A), with frequency varying from 1 to 50 MHz in steps of 1 MHz, and peak-to-peak amplitudes, $A_{mod} = 0.8\%$ and 1.6% of I_{th}. Only for the higher modulation amplitude and the lower I_{DC} the laser operates momentarily below the solitary threshold I_{th}, in a range where the LFFs are still observed, and no remarkable qualitative difference due to this fact appears. For all other values of modulation amplitude and I_{DC} the laser current is always above I_{th}. The experiment was controlled by a LabVIEW program that acquires the time series, detects the spikes, and calculates the inter-spike-intervals (ISIs) until a minimum of 60,000 ISIs are recorded. Then, the program changes the modulation frequency and/or amplitude, waits 10 seconds to let transients die away, and the process is repeated.

IV. RESULTS AND DISCUSSION

The results of our research were published in 5 articles in high-impact journals in the fields of photonics and nonlinear physics: one *New Journal of Physics* (impact factor: 3.673), two *Optics Express* (impact factor 3.525), one *IEEE Selected Topics in Quantum Electronics* (impact factor 3.465), and one *IEEE J. Quantum Electronics* (impact factor 2.113). The articles are listed in Section VI.

IV.1. Research topics

Our research continued the work done in the framework of our previous AFOSR three-year project (FA9550-07-1-0238, 2007-2009), and EOARD two-year projects (FA8655-10-1-3075, 2010-2011; FA8655-12-1-2140 2012-2013) and focused on:

1. Nonlinear dynamics of semiconductor lasers with optical injection
2. Nonlinear dynamics of semiconductor lasers with optical feedback

In the next subsections we present the main achievements in each topic and the related publications.

IV.1.1. Nonlinear dynamics of semiconductor lasers with optical injection

Main achievements:

- Characterization of polarization hysteresis and bistability induced by frequency detuning in orthogonally injected VCSELs: we found numerically appropriated injection conditions such that the orthogonal polarization turns on and locks to the injected field; near the two locking boundaries there are narrow or wide hysteresis cycles, and even irreversible switching. These results are in agreement with recent observations.
- Characterization of the role of the modulation phase in the generation of optical rogue waves: via model simulation we found appropriate modulation conditions for which rogue waves only occur within a well-defined

interval of values of the modulation phase, i.e., there is a "safe" window of modulation phases where extreme pulses are unlikely.

Related publications: References 1 and 2 Section VI.

IV.1.2. Nonlinear dynamics of semiconductor lasers with optical feedback

Main achievements:

- A novel measure computed from observed data (the laser polarization-resolved output) based on symbolic analysis allows inferring an early warning signal of an abrupt transition induced by a time-varying parameter (the laser pump current): the polarization switching in a VCSEL subject to polarized optical feedback. This measure could be tested for the prediction of other abrupt events, such as extreme optical rogue waves.

- Characterization of the role of the modulation frequency and of the intrinsic spike rate in the serial temporal correlations present in sequences of optical spikes: detection of noisy phase-locking in observed data, in very good agreement with predictions of the Lang-Kobayashi model.

Related publications: References 3, 4 and 5 in Section VI.

IV.2. PhD thesis

TITLE: Experimental and numerical study of the symbolic dynamics of modulated semiconductor lasers with optical feedback.
STUDENT: Taciano Sorrentino
UNIVERSITY: Universitat Politecnica de Catalunya
FACULTY/SCHOOL: Departament de Fsica i Enginyeria Nuclear
YEAR: July 2015

IV.3. Science communication

Invited talks

1. Dynamics Days Europe 2014, Symposium on Extreme Events. Bayreuth, Germany, September 2014.
   Extreme optical pulses: origin, predictability and control.
   Presented by C. Masoller

2. Short Thematic Program on Delay Differential Equations, The Fields Institute, Toronto, Canada, May 2015.
   Optical spikes in the delayed Lang-Kobayashi equations: interplay of modulation and delay.
   Presented by C. Masoller

3. 2015 SIAM Conference on Dynamical Systems, Minisymposium on Rare Events in Stochastic Systems, Snowbird, Utah, US, May 2015.
   Influence of Periodic Modulation in Rare and Extreme Optical Pulses.
   Presented by C. Masoller

Oral contribution

Conference on Lasers and Electro-Optics - CLEO/Europe, Munich, Germany, June 2015.
Control of Rogue Waves in Optically Injected Semiconductor Lasers, presented by C. Masoller.

Poster contribution

Dynamics Days Europe 2014, Bayreuth, Germany, September 2014.
Experimental control of laser optical spikes via direct current modulation, presented by C. Quintero-Quiroz.

IV.4. Collaborators and people involved

We have continued our collaboration with Dra. Maria Susana Torre (Universidad Nacional del Centro de la Provincia de Buenos Aires, Tandil, Argentina on hysteresis and bistability in orthogonally injected VCSELs); and Dr. Yanhua Hong (Bangor University, Wales) and Dr. Stephane Barland (Institut Non-Lineaire de Nice, France) on early warning signals of abrupt transitions (VCSEL polarization switching).

V. CONCLUSIONS

The results obtained were published in 5 high-impact journal papers and were presented as invited or contributed talks in several international conferences and workshops. The research involved the work of two PhD students at UPC and two undergrads that performed a summer internship in our lab. A PhD student recently defended his thesis (Sorrentino, UPC July 2015).

VI. REFERENCES

1. M. F. Salvide, C. Masoller and M. S. Torre, *Polarization switching and hysteresis in vertical-cavity surface-emitting lasers subject to orthogonal optical injection*, IEEE J. Quantum Electron. 50, 248 (2014).

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3. C. Masoller, Y. Hong, S. Ayad, F. Gustave, S. Barland, A. J. Pons, S. Gomez, and A. Arenas, *Quantifying sudden changes in dynamical systems using symbolic networks*, New Journal of Physics 17, 023068 (2015).

4. T. Sorrentino, C. Quintero-Quiroz, A. Aragoneses, M. C. Torrent, and C. Masoller, *The effects of periodic forcing on the temporally correlated spikes of a semiconductor laser with feedback*, Optics Express 23, 5571 (2015).

5. T. Sorrentino, C. Quintero-Quiroz, M. C. Torrent, and C. Masoller, *Analysis of the Spike Rate and Spike Correlations in Modulated Semiconductor Lasers With Optical Feedback*, IEEE J. Sel. Top. Quantum Electron. (special issue on Semiconductor Lasers) 21, 1801107 (2015).

VII. LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

LFF –Low-Frequency Fluctuations

VCSEL –Vertical Cavity Surface Emitting Laser

ISIs –Inter-Spike-Intervals

UPC –Universitat Politecnica de Catalunya